THE POTENTIAL OF CONTINUOUS OPERATING NETWORK OF SPACE-BASED RADIO NAVIGATION SATELLITES FOR WEATHER INFORMATION RETRIEVAL

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Abstract: Global Positioning System (GPS) is an emerging satellite-based radio navigation technology for climate analysis and space weather forecasting. The basis for the ground-based GPS atmospheric sensing involves resolving the excess group delay of the GPS signals in terms of the atmospheric parameters using data collected by geodetic-quality GPS receivers at a fixed point on the ground. Given the imperativeness of accurate predictions on the atmospheric profiles in planning a great variety of human endeavours, this paper highlights the establishment of GPS continuously operating reference stations (CORS) network infrastructure for weather information retrieval. In addition to the overviews of the GPS, the principle and the related modelling of GPS ground-based atmospheric sensing, further discussion includes the feasibility of this state-of-the-art technology in substitute of other remote sensing approaches. Based on studies conducted abroad, GPS CORS is sufficiently adequate to augment the analysis of severe weather and relevant environmental issues. In addition to its unprecedented spatial coverage, GPS CORS provides long-term practicality, accuracy and all weather operability for continuous retrieval of the spatial and temporal variability of the Earth's atmosphere.

Keywords: *CORS; GPS; Weather.*

1.0 Introduction

Variability of weather conditions affects not only to the agricultural cycle and human well-being, but also to many economic and societal activities. Prolonged and destructive droughts over the grain and paddy belts, for example, lead to shortages of food whereas heavy precipitation, thunderstorms, floods and hurricanes on the other hand, account for huge losses of farmland and crops, housing and infrastructure. To accurately monitor and predict the state of the weather, with the ultimate aim of minimizing losses of life and property, knowledge of the quantitative state of the atmosphere is of paramount importance. To satisfy the needs of meteorologists, climatologists and specialists in marine activities, forestry, urban and rural planning, agriculture, aviation and other fields, a variety of atmospheric sensing platforms and techniques have been initiated during the past decades. These include the establishment of Global Observing System (GOS) under World Weather Watch (WWW) by the World Meteorological Organization (WMO).

GOS has been a major mechanism for providing continuous and reliable observational data worldwide. The backbone of GOS is a surface based subsystem that is operated mainly by the national meteorological service like Malaysia Meteorological Department (MMD) and a space based subsystem that is operated by either national or international space agencies. At present, the most commonly used atmospheric sensing approaches in Malaysia are weather balloons (or radiosondes), surface observation stations, Radio Detection and Ranging (RADAR) and satellite images (see Figure 1).

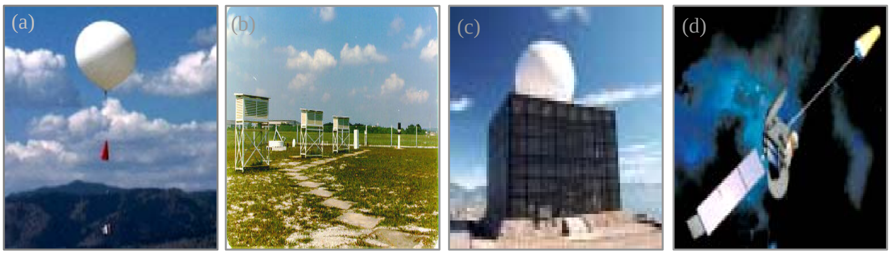

Figure 1: Overviews of (a) radiosonde (b) surface observation compound (c) RADAR and (d) meteorological satellite

However, there are certain limitations with the current suite of these commonly-used atmospheric sensors to remotely sense the spatial and temporal variability of the Earth's atmosphere. These include the inhomogeneity of spatial and temporal coverage, high acquisition and maintenance cost, data discontinuities, intensive labour requirement and changes of instruments to instrumental drift problems (Coster et al. 1996 and Guichard et al. 1999). As far as satellite imageries are concern, it is apparently inadequate in Malaysian region due to the severe cloud problem associated with the meteorological infrared sensors (Loganathan et al. 2004). Although the use of microwave radiation sensors on the other hand is not affected by the presence of clouds, the atmospheric information retrieved using this approach is only available over the ocean surfaces (Kishtawal 2003).

Given the imperativeness of accurate predictions on the state of the weather in planning a great variety of human endeavours, there has been a resurgence of interest towards the use of Global Positioning System (GPS) for the purpose of weather information retrieval worldwide. As GPS technology is yet relatively new to the Malaysian weather forecasting community, this paper highlights the establishment of this multi satellites continuously operating reference stations (CORS) network infrastructure for the purpose of weather information retrieval. In addition to the overviews of the GPS, the principle and the related modelling of GPS ground-based atmospheric sensing, further discussion includes the feasibility of this state-of-the-art technology in substitute of other remote sensing approaches.

2.0 Global Positioning System

GPS is a space-based radio navigation satellites system. Initially developed for United States' military purposes, GPS has been in full operational capability (FOC) since 17 July 1995, with 24 Block II/IIA satellites. The orbital planes of the satellites are inclined relatively at 55˚ to the equator with an orbital radius of 26,600 km. Located at about 20,200 km above the Earth's surface, the satellites are distributed in six Earth-centred orbital planes with four satellites in each plane. In 2008, the GPS space segment however has recently increased to 32 satellites constellation.

Given the use of L-band frequency gives acceptable received signal power with reasonable satellite transmission power levels and Earth coverage satellite antenna patterns, each satellite controlled by atomic clock transmits fundamental L-band frequency of 10.23 MHz. At present, two carrier radio signals namely the L1 band carrier (1575.42 MHz) and L2 band carrier (1227.60 MHz) are coherently derived from this fundamental frequency, though a new frequency L5 (1176.45 MHz) may be implemented in the near future. The carrier wavelength for L1 and L2 carriers are 19.03 cm and 24.42 cm respectively. Modulated with ranging codes and navigation (data) message, Figure 2 illustrates the present composition of GPS satellite signal.

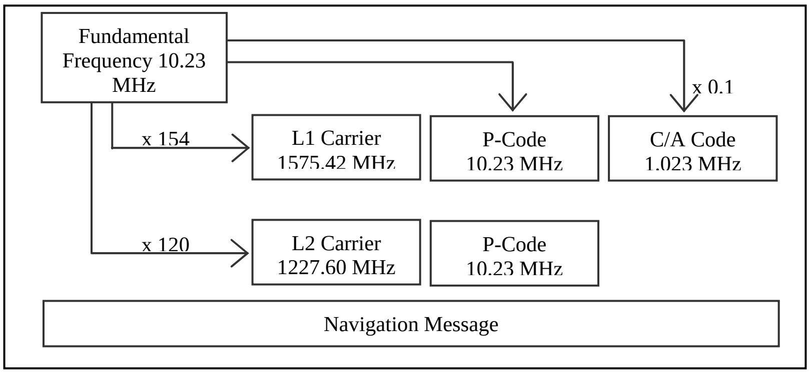

Figure 2: GPS satellite signal composition

3.0 Ground-based GPS Atmospheric Sensing

3.1 The Principle

The basis for ground-based GPS atmospheric sensing involves resolving the signal propagation delay in terms of atmospheric parameters using data collected by geodetic-quality GPS receivers at a fixed point on the ground (see Figure 3). As GPS signals propagate to the ground receiver, they are affected by changes in the refractive indices within the signal path caused by the ionosphere and the neutral atmosphere. Correcting for the dispersive ionospheric contribution, the non dispersive contribution from the electric neutral atmosphere can be obtained in which is mainly induced by dry air, water vapour, clouds and rain and is proportional to the masses of the specific components along the ray path. Although it is often considered a nuisance by geodesists and surveyors in high accuracy positioning, the signal propagation delay can be exploited to retrieve appreciable weather information. These include precipitable water vapour (PWV) in which can be further used as a precursor for rainfall, thunderstorm, flash flooding and seasonal monsoon event. In addition, accurate PWV estimation can also be used to characterize other precipitation such as hail, sleet, freezing rain, snow and ice crystals. Further discussion on the theory of signal propagation delays induced by dry air, hydrometeors and other particulates (e.g. sand, dust, aerosols and volcanic ash) in the atmosphere is given in Solheim et al. (1999).

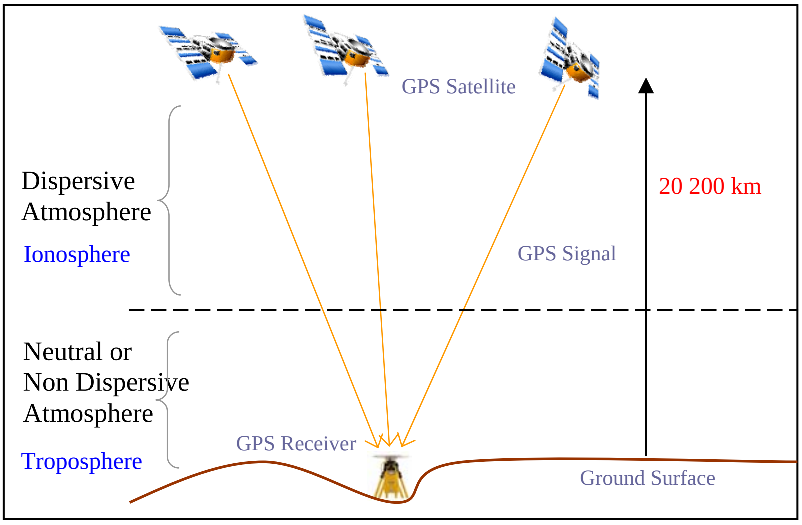

Figure 3: GPS ground-based atmospheric sensing

As far as the non dispersive component of the atmospheric refractivity is concerned, the refractivity can be grouped into the hydrostatic and the wet components. The hydrostatic component characterizes the effect of the induced dipole moment of the dry constituent. The wet component on the other hand characterizes the dipole moment of water vapour, along with the orientation effects of the permanent dipole moment of water molecules. The total refractivity can be expressed as (Solheim et al. 1999):

$$N(f) = N_0 + N'(f) + iN''(f) \qquad (1)$$

where f is the signal frequency in hertz, N_0 and $N'(f)$ are the non-dispersive and dispersive components of refractivity associated with the real part of the permittivity, and $N''(f)$ is the attenuation which is related to the imaginary part of the permittivity. Based on Eq. (1), the dependency of phase refractivity on atmospheric variables can be expressed as (Kursinski et al. 2000):

$$N = 77.6\frac{P}{T} + 3.73\times10^{5}\left(\frac{P_w}{T^2}\right) - 4.03 n_e / f^2 \tag{2}$$

where P is the total atmospheric pressure in mbar, P_w is the partial pressure of water vapours in mbar, T is the temperature in degrees Kelvin, and n_e is the free electron density in electrons per cubic metre. The delay in the GPS signal arrival caused by the refractive index can then be used to estimate an equivalent zenith total delay (ZTD). ZTD is the delay experienced by the GPS signal caused by the refractivity effect of the non dispersive atmosphere. ZTD is distance-dependent that increases when the baseline length between two GPS stations increases. Similarly, ZTD induces discrepancies in the GPS derived positions and varies with changes on the meteorological conditions. Based on series of investigations made within Johore RTK network, it is noted that maximum residuals in Easting, Northing and Height components due to tropospheric effect are 68.880 cm, 68.970 cm and 119.100 cm respectively (Yahya and Kamarudin 2007; Dodo et al. 2008). Reaching to the minimum and maximum RMS value of 16.8 and 29.2 respectively, GPS Height component is by far the most affected component compared to the Horizontal components (Yahya and Kamarudin 2008a). The general mathematical modelling for ZTD is given by Thayer (1974) as:

$$ZTD = \underbrace{\left(k_1\cdot\left(\frac{P_d}{T}\right)\cdot Z_d^{-1}\right)}_{1^{st}\ \text{term}} + \underbrace{\left(k_2\cdot\left(\frac{e}{T}\right) + k_3\cdot\left(\frac{e}{T^2}\right)\right)\cdot Z_w^{-1}}_{2^{nd}\ \text{term}} \tag{3}$$

where $Z_{d/w}^{-1}$ is the inverse compressibility factors for dry and wet air, P_d is the dry pressure; P_d = p – e with p being the total pressure (measured quantity) and e is the partial pressure of water vapour in mbar. $k_{1\ldots3}$ on the other hand are refraction constants. Details on the most significant evaluations of the refractivity constants can be referred in Yahya and Kamarudin (2008b). Based on Eq. 3, the 1st term characterizes the effect of the induced dipole moment of the dry constituent usually referred to as zenith hydrostatic delay (ZHD). The 2nd term in which characterizes the dipole moment of water vapour, along with the orientation effects of the permanent dipole moment of water molecules is often called as zenith wet delay (ZWD). ZWD is entirely due to the presence of water vapour and that liquid water and ice does not contribute to the effect. As ZHD contributes to about 90% of the ZTD, ZWD on the other hand contributes to the remaining 10% of the effect (Janes et al. 1989). PWV is basically the conversion of ZWD by means of measured surface pressure and temperature and the hydrostatic assumption. Based on Eq. 3, the retrieval of PWV can be made using the following derivation (Bevis et al. 1994):

$$PWV = k \times \left[\left(k_2 \cdot \left(\frac{e}{T} \right) + k_3 \cdot \left(\frac{e}{T^2} \right) \right) \cdot Z_w^{-1} \right] \tag{4}$$

$$k = \left[10^{-6} \cdot \left(k_2 + \frac{k_3}{T_M} \right) \cdot R_w \cdot \rho_w \right]^{-1} \tag{5}$$

where ρ_w is the water density, R_w is the specific gas constant of water vapour and T_m is the atmospheric weighted mean temperature. Due to its varying value at different geographical locations, appropriate estimation of T_m is vital to ensure the quality of PWV quantification. Details on the most significant evaluations of the atmospheric weighted mean temperature can be referred in Yahya and Kamarudin (2008b).

3.2 The Infrastructure

Taking the benefit of existing GPS CORS networks, there has been a resurgence of interest towards the use of the GPS infrastructure for weather and environmental studies. Mostly integrated with radiosondes or surface meteorological observations, these ground-based GPS networks include the U.S. National Oceanic and Atmospheric Administrations (NOAA) Ground-Based GPS Integrated Precipitable Water (GPS-IPW) Network (Wolfe and Gutman 1999). In addition, there are also studies been made in Canada through the Westford Water Vapour Experiment (WWAVE) (Coster et al. 1996); Sweden through the Goteborg GPS network (Nilsson and Gradinarsky 2006); Australia through the Australian Regional GPS Network (ARGN) (Feng et al. 2001); Japan through the GPS Earth Observing Network (GEONET) (Iwabuchi et al. 2000) and Africa through the use of African IGS Network (Walpersdorf et al. 2007).

Based on studies conducted abroad, GPS CORS network provides unprecedented spatial coverage and continuous PWV estimation with higher temporal resolution of 30 seconds to 30 minutes (Feng et al. 2001). It is estimated that inter-station spacing within a CORS network should not be more than 50-70 km to accurately quantify the PWV for weather and environmental purposes (MacDonald and Xie, 2000). As far as the multipath and the signal interference are concerned, it is also important to have a GPS observation site that is stable and far from any source of water, obstruction and electromagnetic fields. To augment the modelling of the ZWD for GPS-PWV estimation, radiosonde or surface meteorological sensor need to be place next to the GPS CORS. Bai and Feng (2003) however, shows that by using appropriate interpolation method based on existing meteorological data network located at tens of kilometres apart from GPS stations, GPS-PWV estimation agree with Radiosonde-PWV estimation at an average mean difference of 0.604 mm and RMS of 1.74 mm for 195 site comparisons. Here, rather than acquiring new meteorological sensors to be attached to GPS receivers, there is a possibility of integrating GPS CORS and existing meteorological sensor infrastructure even when being located far from one to another. Figure 4 illustrates the configuration of GPS-PWV CORS network located in Bartlett, NH.

Figure 4: GPS-PWV configuration in Bartlett, NH

3.2.1 NOAA GPS-Met Project

NOAA GPS-Met Project is an extensive collaboration between the National Oceanic and Atmospheric Administration's (NOAA) Forecast Systems Laboratory (FSL) and Environmental Technology Laboratory (ETL), with the University NAVSTAR Consortium, University of Hawaii, Scripps Institution of Oceanography and NOAA's National Geodetic Survey (NGS) Laboratory. To date, NOAA GPS-Met consists of a network of about 500 CORS sites across the U.S., Canada, Mexico and the Caribbean. The purpose of this project is to evaluate the engineering and scientific bases for ground-based atmospheric sensing.

In addition to demonstrate the feasibility of using ground-based atmospheric sensing for improved weather forecasting, climate monitoring and satellite sensor calibration/validation; the aim of this project is to transform the observing system technology into operational use. It is noted that the NOAA GPS-Met network consists of the integration of the geodetic-grade GPS receivers and the surface meteorological sensors. Based on the studies conducted by Wolfe and Gutman (1999), the NOAA GPS-

Met operational system tends to monitor atmospheric water vapour in near–real time with accuracies (<1.5 cm) comparable to radiosondes and water vapour radiometers. Figure 5 illustrates the network design of the NOAA GPS-Met Project.

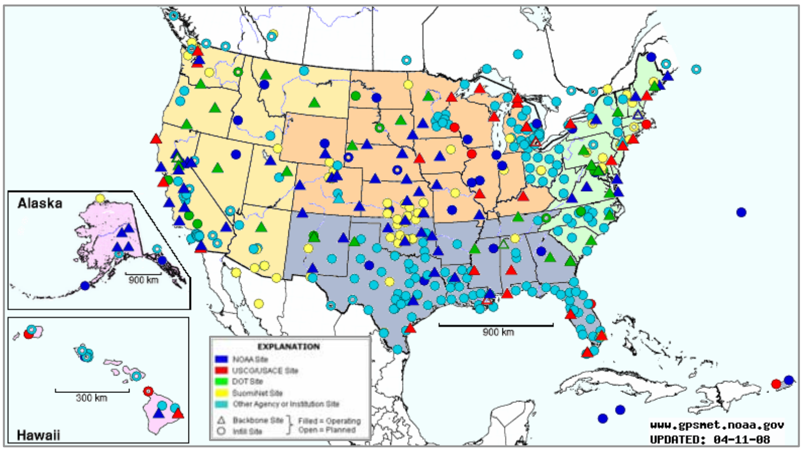

Figure 5: NOAA GPS-Met Project

3.2.2 GPS Earth Observing Network (GEONET)

GEONET is a GPS CORS network operated by the Geographical Survey Institute (GSI) of Japan since 1994. Equipped with high accuracy dual-frequency receivers, it was principally developed for crustal motion and deformation studies. Currently, there are about 1224 GEONET stations with a mean separation of 17 km. As far as GPS meteorology is concerned, ground-based atmospheric sounding in Japan has been developed along with GEONET. Although GEONET stations do not have in-situ pressure and temperature observations, the GPS-PWV retrieval for assimilation into NWP has been found to be of high accuracy and in reasonable agreement with radiosonde data (Iwabuchi et al. 2000). Based on studies conducted by Iwabuchi et al. (2006), Figure 6 illustrates the example of ZTD, ZWD and PWV estimation over GEONET infrastructure.

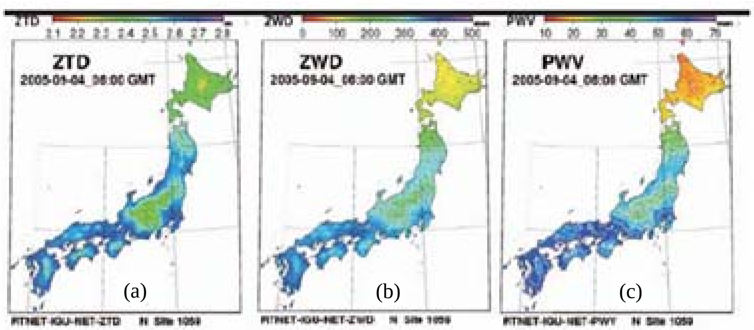

Figure 6: Overviews of GEONET (a) ZTD (b) ZWD and (c) PWV estimation

3.2.3 GPS Atmosphere Sounding Project (GASP)

GASP project consists of data generation, transmission and analysis components. Moderated by the GeoForschungsZentrum (GFZ), it was financed by the Helmholtz Association of German Research Centre. Began in 2000, currently there are over 200 sites mostly from the Satellite Positioning Service (SAPOS) of the German National Survey, with an average separation of about 50 km. GASP aims to develop a system for the operational determination of PWV and to assimilate these data into NWP models. Although surface meteorological data are available at some GPS stations, for most of the sites, the required pressure and temperature data have to be interpolated using the synoptic sites of the German Weather Service (about 200 sites). According to Gendt et al. (2003), the accuracy of the interpolation ranges from about 0.3 hPa to 1.0 hPa.

4.0 Conclusion

GPS is an emerging state-of-the-art satellite-based radio navigation technology for weather and environmental studies. It is based on the transmitted GPS satellite radio signals that can be used to measure atmospheric profiles of refractivity. Atmospheric refractive indices in general cause an excess group delay of the GPS signals in relation to free-space propagation. Taking the benefit of existing GPS CORS networks worldwide, there has been a resurgence of interest towards the use of GPS in substitute to other commonly-used atmospheric remote sensing techniques. It is noted that there are lots of advantages using GPS CORS network for the retrieval of weather information. Based on studies conducted abroad, GPS CORS is sufficiently adequate to augment the analysis of severe weather and relevant environmental issues. In addition to its unprecedented spatial coverage, GPS CORS provides long-term practicality, accuracy and all weather operability for continuous retrieval of the spatial and temporal variability of the Earth’s atmosphere.

References

Bai, Z., & Feng, Y. (2003). GPS Water Vapor Estimation Using Interpolated Surface Meteorological Data from Australian Automatic Weather Stations. *Journal of Global Positioning Systems*.

Bevis, M., Businger, S., & Chiswell, S. (1994). GPS Meteorology: Mapping Zenith Wet Delays on to Precipitable Water. *Journal of Applied Meteorology 33*, 379-386.

Coster, A.J., Niell, A.F., Solheim, F.S., Mendes, V.B., Toor, P.C., Langley, R.B., & Ruggles, C.A. (1996). The Westford Water Vapor Experiment: Use of GPS to Determine Total Precipitable Water Vapor. *ION 52nd Annual Meeting*. Cambridge, MA.

Dodo, J.D., Yahya, M.H., & Kamarudin, M.N. (2008). The Effect of Tropospheric Delay on GPS Height Differences Along the Equator. *Surveying and Land Information Science 68(3)*.

Feng, Y., Bai, Z., Fang, P., & Williams, A. (2001). GPS Water Vapor Experimental Results From Observations of the Australian Regional GPS Network (ARGN). *A Spatial Odyssey: 42nd Australian Surveyors Congress*, 18 pp.

Gendt, G., Dick, G., Reigber, C., Tomassini, M., & Liu, Y. (2003). Demonstration of NRT GPS Water Vapor Monitoring for Numerical Weather Prediction in Germany. In *International Workshop on GPS Meteorology*. Tsukaba, Japan.

Guichard, F., Parsons, D.B., & Miller, E.R. (1999). The Radiative Impact of a Correction for a Sonde Humidity Bias Over the Tropical Western Pacific. *Ninth ARM Science Team Meeting*, pp. 1-7. San Antonio, Texas.

Iwabuchi, T., Naito, I., & Mannoji, N. (2000). A Comparison of Global Positioning System Retrieved Precipitable Water Vapor with the Numerical Weather Prediction Data over the Japanese Islands. *Journal of Geophysical Research 105(4)*, 4573-4585.

Iwabuchi, T., Rocken, C., Mervart, L., & Kanzaki, M. (2006). Nowcasting and Weather Forecasting. *Location* 44-53.

Janes, H.W., Langley, R.B., & Newby, S.P. (1989). A Comparison of Several Modes for the Prediction of Tropospheric Propagation Delay. *Fifth International Geodetic Symposium on Satellite Positioning*. Las Cruces, New Mexico.

Kishtawal, C.M. (2003). Meteorological Satellites. *Training Workshop* (Sivakumar, M.V.K., et al., Eds.). Dehra Dun, India

Kursinski, F.R., Hajj, G.A., Schofield, J.T., Linfield, R.P., & Hardy, K.R. (1997). Observing the Earth's Atmosphere with Radio Occultation Measurements using the Global Positioning System. *Journal of Geophysical Research 102*, 23429-23465.

Loganathan, G.V., S.Gorugantula, Kibler, D.F., Keighton, S.J., & Gillen, M. (2004). Use of GPS Technology for Short-term Rainfall Prediction. In, pp. 1-9. ASCE.

MacDonald, A.E., & Xie, Y. (2000). On the Use of Slant Observation from GPS to Diagnose Three-dimensional Water Vapor Using 3DVAR. *Fourth Symposium on Integrated Observing Systems*, pp. 62-73. American Meteorological Society, Long Beach, CA.

Nilsson, T., & Gradinarsky, L. (2006). Water Vapor Tomography Using GPS Phase Observations: Simulation Results. *IEEE Transactions on Geoscience and Remote Sensing 44(10)*, 2927-2941.

Solheim, F.S., Vivekanandan, J., Ware, R.H., & Rocken, C. (1999). Propagation Delays Induced in GPS Signals by Dry Air, Water Vapor, Hydrometeors and Other Particulates. *Journal of Geophysical Research 104(D8)*, 9663-9670.

Thayer, G.D. (1974). An Improved Equation for the Radio Refractive Index of Air. *Radio Science 9*, 803-807.

Walpersdorf, A., Bouin, M.N., Bock, O., & Doerflinger, E. (2007). Assessment of GPS Data for Meteorological Applications Over Africa: Study of Error Sources and

Analysis of Positioning Accuracy. *Journal of Atmospheric and Solar-Terrestrial Physics 69(2007)*, 1312-1330.

Wolfe, D.E., & Gutman, S.I. (1999). Developing an Operational, Surface-Based, GPS, Water Vapor Observing System for NOAA: Network Design and Results. *Journal of Atmospheric and Oceanic Technology 17*, 426-424.440.

Yahya, M.H., & Kamarudin, M.N. (2007). The Impact of Tropospheric Delay Towards The Accuracy of GPS Height Determination. *Joint International Symposium and Exhibition on Geoinformation and International Symposium on GPS/GNSS (ISG-GNSS 2007)*. Johor Bahru, Malaysia.

Yahya, M.H., & Kamarudin, M.N. (2008a). Analysis on the Residuals in GPS Measurement due to Tropospheric Effect at the Equatorial Region. *International Conference on Civil Engineering (ICCE08)*. Pahang, Malaysia.

Yahya, M.H., & Kamarudin, M.N. (2008b). Retrieval of Weather Information for Climate Change Monitoring Using Ground-Based GPS Network. *Third Regional Symposium on Environment and Natural Resources (RSENR 08)*. Kuala Lumpur, Malaysia.